13th IEEE Pulsed Power Conference, Las Vegas, NV, June 17-22, 2001. IEEE, New York, NY p 710 (2002).

DEVELOPMENT OF A DURABLE, LARGE AREA CATHODE FOR REPETITIVE, UNIFORM ELECTRON BEAM GENERATION*

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Abstract

Electra [1] is a large aperture krypton-fluoride laser under development for inertial fusion energy research. The laser will require dual 500 kV, 36 A/cm^2, uniform electron beams operating at 5 Hz. Experimental studies have been performed to develop a ~3000 cm^2 cathode capable of generating a 110 kA, 100 ns flat top beam pulse with minimal current density variation (<10%), fast rise time (<40 ns), negligible gap closure (<1 cm/μs), and long lifetime (ultimately 10^8 shots). Time resolved electrical and optical data from the study of various dielectric fiber, carbon, and metal/dielectric cathodes will be discussed.

I.INTRODUCTION

Electra is a krypton fluoride (KrF) laser that will be used to develop the technology necessary for an inertial fusion energy (IFE) power plant. The laser gas will be pumped from two sides by rectangular cross-section electron beams at a repetition rate of 5 Hz. The 500 kV, 100 ns flat-top electron beams are emitted from 3000 cm^2 cathodes in a ~5 Ω vacuum diode which is immersed in an external magnetic field of 0.14 T (~2.2 times the beam self-field).

In order to form the high quality laser pulses and meet the efficiency required for IFE, the following electron beam generation conditions must be met: current rise time must be less than 40 ns, gap closure velocity must be less than 1 cm/μs, current density variation must be ≤10%, and emitter lifetime must approach 10^8 shots. The time it takes for the current pulse to reach peak value is critical for two reasons. First, the lower energy electrons emitted during the rise of the pulse may not gain enough energy to pass through the titanium anode foil that separates the high pressure laser gas from the vacuum diode. These electrons deposit their energy in the foil, which could result in overheating and possible failure of the foil. Second, slow excitation of the laser gas contributes to unwanted amplified spontaneous emission that can result in a laser "pre-pulse" on the IFE target. The voltage pulse flat-top must be maintained for 100's of ns to assure temporal uniformity of the laser pulse. The generation of dense cathode and/or anode plasmas can lead to gap closure and impedance collapse again resulting in anode foil overheating and poor system efficiency. The emitted electron beam must maintain a minimal variation in current density to i) avoid uneven deposition in the laser gas which may result in spatial non-uniformities in the laser pulse and ii) prevent local overheating of the anode foil. Finally, for power plant requirements, the cathodes must be durable enough to generate uniform electron beams for nearly 2 years at 5 Hz (3x10^8 shots). The cathode must also function in a strong external magnetic field that prevents the rectangular cross-section beam from distorting as it propagates. The above requirements, coupled with the additional IFE durability, simplicity, and cost considerations, suggest that cold cathodes may be the best option.

Comprehensive studies [2][3] have been conducted on several types of cold cathodes at comparable current density (10's of A/cm^2), electric field strength (10^5 V/cm), pulse width (100's of ns), and repetition rate. For the application here, the effects of external magnetic field, higher current, and larger area must be examined. The issue of uniformity must also be more closely studied. Dielectric fiber (velvet) cathodes have been researched in detail [4] and provide excellent uniformity and turn-on time. Questions remain about the material longevity and gap closure after 10^4 shots. Carbon fiber cathodes have been studied extensively [5][6] but again, there is little data in the literature about emission uniformity for cathode areas of 1000's of cm^2 in external magnetic fields. Some research has been done on metal/dielectric cathodes [7] indicating excellent longevity, but this work was conducted using pulse widths of 10's of ns.

For this work, the emission characteristics of eighteen different cathode materials were observed in operation on Electra. Most were quickly rejected as viable cathodes for IFE due to poor rise time and/or uniformity. Here, three cathodes that initially exhibited viable rise time and uniformity are examined: dielectric fiber (Eagle brand-double velvet, 18 μm dia., 1.5 mm height, 4.4% coverage), carbon fiber (10 μm dia., 10 mm

* Work supported by the U.S. Department of Energy
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Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **2002**	2. REPORT TYPE	3. DATES COVERED **00-00-2002 to 00-00-2002**
4. TITLE AND SUBTITLE **Development of a Durable, Large Area Cathode for Repetitive, Uniform Electron Beam Generation**		5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)		5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Naval Research Laboratory,Plasma Physics Division,Code 6730,Washington,DC,20375**		8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR’S ACRONYM(S) 11. SPONSOR/MONITOR’S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES
13th IEEE Pulsed Power Conference, Las Vegas, NV, June 17-22, 2001. IEEE, New York, NY p 710 (2002)

14. ABSTRACT
Electra [1] is a large aperture krypton-fluoride laser under development for inertial fusion energy research. The laser will require dual 500 kV, 36 A/cm2, uniform electron beams operating at 5 Hz. Experimental studies have been performed to develop a ~3000 cm2 cathode capable of generating a 110 kA, 100 ns flat top beam pulse with minimal current density variation (<10%), fast rise time (<40 ns), negligible gap closure (<1 cm/μs), and long lifetime (ultimately 108 shots). Time resolved electrical and optical data from the study of various dielectric fiber, carbon, and metal/dielectric cathodes will be discussed.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**4**	

height, ~25% coverage), and carbon flock [8] consisting of carbon fibers electrostatically deposited onto aluminum (7.5 μm dia., 1.5 mm height, 2% coverage). A metal/dielectric cathode (berylium copper with ceramic vanes oriented 30° from vertical, spaced at ~1 cm) is also studied in light of its promising lifetime capability.

II. EXPERIMENTAL STUDIES

Each cathode was examined in two separate experiments. First, cathodes were tested using a "diagnostic anode" (Fig. 1) that allowed direct access for electron beam measurements. Radiachromic film monitored time-integrated beam uniformity. A 4-frame, micro-channel plate intensified, gated optical imager (GOI) gave time-resolved uniformity capturing light from a fast scintillator. An array of Faraday cups measured beam current density and rise time. The diode voltage and current were measured with a capacitive probe and a Rogowski coil, respectively. A 1 mil thick, aluminized Kapton foil, which is transparent to electrons of energy greater than ~20 keV, served as the anode. Because of power dissipation issues, data taken with the diagnostic anode plate is based on groups of single shots taken at ≤1 Hz repetition rate. This was sufficient to initially assess cathode rise time, turn-on, and uniformity. In the second set of experiments, the diagnostic anode was replaced with an aluminum "cooled anode" and the cathodes were tested under full operation at 5 Hz. Rise time and gap closure issues were examined as a function of the number of shots using the diode voltage and current monitors and a cold cathode gauge to monitor diode vacuum. The uniformity of the beam after a number of shots was measured using radiachromic film positioned with an in-vacuum scrolling mechanism. For all cases, the cathode dimensions were 27 cm x 97 cm, the AK gap was 5.2 cm, and the external magnetic field was 0.14 T. A 4000 l/s cryo-pump established the initial diode vacuum at ≤ 8E-6 Torr.

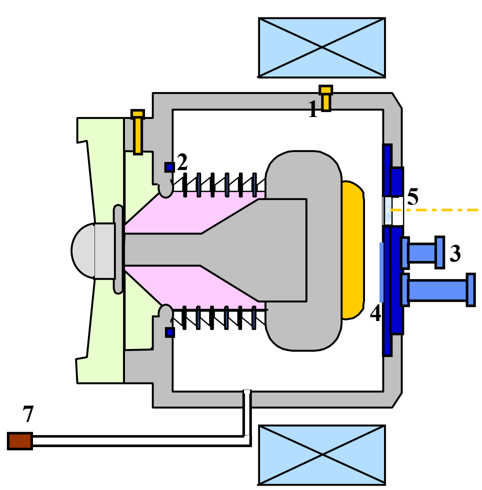

Figure 1. Schematic of Electra diode showing 1-capacitive voltage monitor, 2-Rogowski monitor, 3-Faraday cup, 4-radiachromic film, 5-converter-scintillator, 6-GOI camera, and 7-vacuum gauge.

A. Cathode Turn-on With Diagnostic Anode

The rise of a typical, normalized diode current waveform is shown for each cathode in Fig. 2. The 10-90% rise time for the velvet was 40 ns; the carbon flock, carbon fiber, and metal/dielectric displayed a ~55 ns rise time. Typically in the diode, E=100 kV/cm and dE/dT≈8-10 kV/(cm•ns). For the velvet cathode, the initial turn-on of the diode current occurred when the diode voltage was ~10 kV; the carbon fiber and carbon flock turned on at 20-25 kV. The metal/dielectric cathode exhibited no turn-on delay as the current came up simultaneously with the voltage. Note that the data is based on single shots and the turn-on and rise time characteristics may change as the cathodes are conditioned.

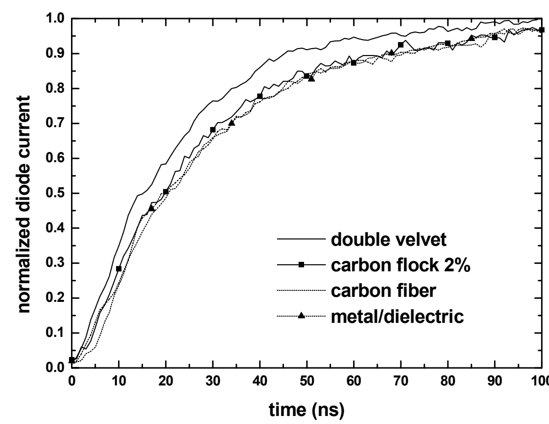

Figure 2. Plot of the normalized diode current showing the rise time for each cathode tested.

B. Gap Closure With Diagnostic Anode

Figure 3 shows a typical time history of the normalized diode impedance for each cathode. A diode current pulse from a velvet cathode is also plotted for reference. The velvet impedance remains nearly constant from the point at which the current reaches 95% of its value out for about 100 ns. The two carbon cathodes exhibit ~10% decrease in impedance over the same interval while the impedance in the metal dielectric case changes by about 20%. No abrupt impedance collapse was seen for any of the four cathodes. Using measurements from three Faraday cups which were located along the central portion of the diagnostic anode plate, the average peak current density is 31.0 A/cm^2 for the velvet, 32.7 A/cm^2 for the carbon flock, 32.1 A/cm^2 for the carbon fiber, and 32.2 A/cm^2 for the metal dielectric. These numbers are within a few percent of the expected 31 A/cm^2 current density derived from the relativistic Child-Langmuir equation. The total charge transferred in the diode is about 0.014 C per pulse in all cases.

C. Uniformity With Diagnostic Anode

A 15 cm x 45 cm sheet of Radiachromic film was mounted 3 mm above the anode surface for time-integrated measurements of single shot uniformity. To avoid exposure from UV and low energy plasma electrons, the film is placed between 25 μm thick titanium foils. Fig. 4 shows a typical 0.1cm wide x 10 cm long "bandout" taken from a scan of a radiachromic film image for each cathode. Since the temporal evolution of the current waveform is nearly the same for all the cathodes, the film exposure is proportional to the beam current density [9]. The uniformity variation σ for velvet is quite good at 4%; the carbon flock is also promising. Emission from the discrete, periodic metal/dielectric cathode structure is clearly reproduced on the film showing a 30% variation. Another, finer scale metal/dielectric cathode was constructed with double the number of emitters in an attempt to improve emission uniformity. This modification reduced the variation to 20%. Faraday cup measurements of current density variation support the time integrated film data. The Faraday cup data also shows that the current density profile is fairly constant during the flat-top portion of the current pulse for all the cathodes. Confirmation of this result was obtained using the GOI. Beam electrons are stopped in a 20 cm x 20 cm 100 μm thick tantalum convertor and the resulting x-rays are then converted to optical light using a fast scintillator (EJ-212). The light is captured at 4 times during the flat-top portion of the current pulse using 2 ns gates. For all the cathodes, lineouts of the raw image show intensity variations comparable to the variations measured by the Faraday cups.

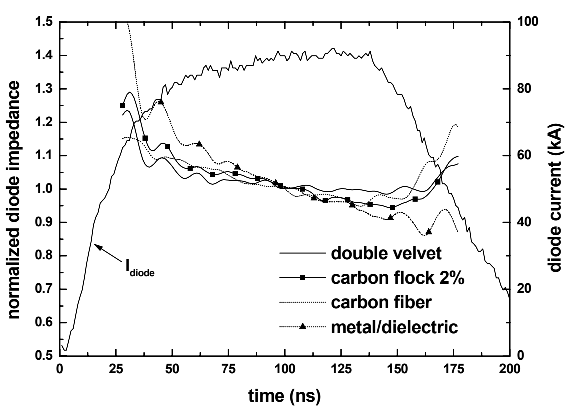

Figure 3. Plot of normalized diode impedance for each cathode tested. The current pulse for a velvet cathode is also plotted for reference.

D. Longevity/Uniformity With Cooled Anode

Initial experiments to study the longevity characteristics of the cathodes were limited to about 3000 shots at 5 Hz due to radiation shielding issues in the laboratory. Figure 5 plots diode voltage traces taken during a 3100 shot run with the carbon fiber cathode. The shape of the voltage pulse is quite constant throughout the run; the diode current decreased slightly from 92 to 90 kA with the rise time remaining constant at about 55 ns. The diode pressure rose from 3E-6 Torr to 2E-5 Torr during the first 100 shots and then remained constant for the duration of the run. A radiachromic film image taken at the 2000th shot indicated a slight improvement in uniformity and a marked decrease in "hot spots". There was no apparent damage or wearing of the carbon fiber material at the end of the run.

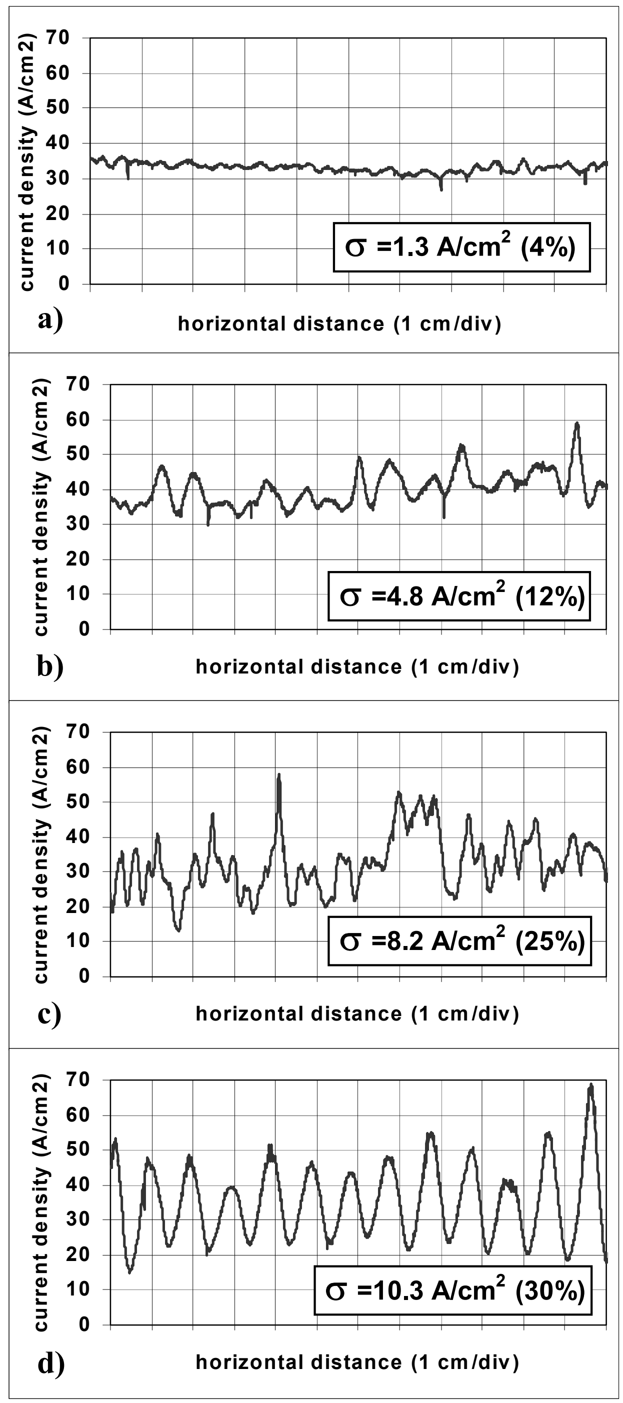

Figure 4. Plot of the time integrated current density derived from radiachromic film scans for a) velvet, b) carbon flock, c) carbon fiber, and d) metal/dielectric cathodes. The current density variation σ is noted in each case.

In a similar 3300 shot run with the carbon flock, the diode voltage was virtually unchanged throughout the run. The diode current amplitude was constant and the rise time improved slightly as the run progressed past 500 shots. The diode pressure rose abruptly to 3.5E-5 Torr and "decayed" to a stable 2.3E-5 Torr after 1000 shots. Uniformity at the 3300th shot was about the same as for a single shot. A few, full-length fibers were found sparsely strewn in the diode after the run. A short, 500 shot run with the velvet cathode showed no changes in diode voltage or current. The diode pressure quickly reached 2E-4 Torr and was constant. Many small velvet fibers were found in the diode after the run. Experiments with the metal/dielectric cathode were limited to ~300 shots due damage of the cooled anode by the high current density at the beam edges [9]. Diode voltage and current were unchanged and the pressure was constant at 2E-5 during the run.

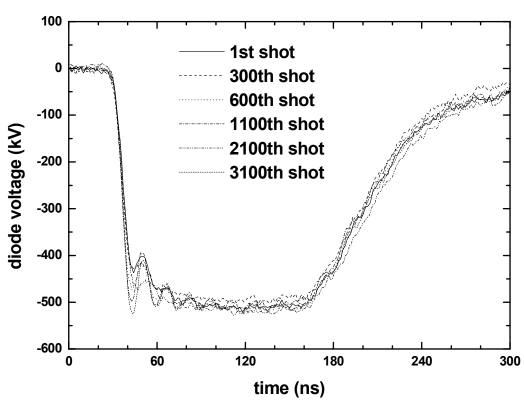

Figure 5. Plot of selected diode voltage traces taken during 3100 shot run at 5 Hz with carbon fiber cathode.

III.SUMMARY

It is clear that the velvet cathode meets the IFE standards for rise time and uniformity but it is not expected to meet the longevity requirements. Rapid gas evolution and fiber debris seen in the short 500 shot run is indicative of gross material loss. These findings are consistent with the extensive data in the literature which concludes that velvet has a finite lifetime of ~10^5 shots [4]. The carbon flock cathode results are promising – gap closure and uniformity characteristics were satisfactory and longevity was not an issue at 3000 shots. However, the rise time must improve. One possibility is to vary the fiber conductivity to study its affect on cathode turn-on. The carbon fiber cathode showed unsatisfactory rise time and uniformity but gap closure and longevity were adequate out to ~3000 shots. Perhaps the uniformity could be improved by adjusting the enhancement ratio, i.e. fiber height and spacing relationship (note that the fiber density was much higher than the velvet or carbon flock). The metal/dielectric cathode rise time must be decreased. Uniformity with this cathode was improved by increasing the number of emitters. More data is needed to assess the longevity of the cathode. For all the cathodes tested, conditioning did not significantly improve rise time, turn-on, or uniformity. To fully assess the cathodes for IFE requirements, longer (10^4-10^5 shot) runs will be necessary. The effects of longer pulses (500 ns) must also be investigated.

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